Comparing Sound Pressure Level Predictions Generated by RUMBLE

to Field Measurements of Atlas V, Falcon 9, and Delta VI Heavy Rockets.

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Bachelor of Science

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ABSTRACT

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RUMBLE is a rocket acoustics modeling software program capable of predicting sound pressure levels of space launch operations. In an attempt to prove the validity of the model, I compare RUMBLE generated LMAX and LAMAX predictions to corresponding field measurements of the Atlas V, Delta IV Heavy, and Falcon 9 rockets. I find RUMBLE under-predicts A-weighted levels by 1.5 dBA. This difference likely comes from RUMBLE's innappropriate use of the Doppler effect in calculating sound pressure levels for rocket acoustics. On average, Z-weighted levels are within 1 dB. From this, I suggest Doppler effects be removed from the the next updated version of RUMBLE. Weather data is not incorporated in this study.

Keywords: sound pressure level, acoustics, rocket, RUMBLE, model, weighting, LMAX, LAMAX

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I acknowledge Blue Ridge Research and Consulting, LLC, for developing RUMBLE, and communicating with us as we learned to use the software program central to this study.

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Chapter 1

Introduction

1.1 Rocket Launch Growth and Emerging Acoustics Research

In the past four years, the world has witnessed a rapid increase in the total number of orbital rocket launches per year. In 2023, there were a record 223 orbital launch attempts, 211 of which were successful. Of those, 117 were U.S. commercial space launches. By the end of 2024, we anticipate over 330 orbital launch attempts worldwide, with the majority expected to come from U.S. commercial space ventures [1]. As we can see in figure 1.1, this accelerated launch cadence is projected to continue both globally and within the United States.

It is no mystery that rockets are loud machines. With the rapidly increasing orbital launch cadence, researchers are raising important questions about the environmental effects of repeated exposure to rocket noise [3]. In human communities, noise ordinances are established to ensure comfortable and safe living standards. These ordinances often include sound level limits for specific times of the day and night. Although efforts have been made to protect wildlife in similar ways, no such regulations have yet been made on rocket launch noise. Rockets can be launched at any time of the day or night on any day of the year.

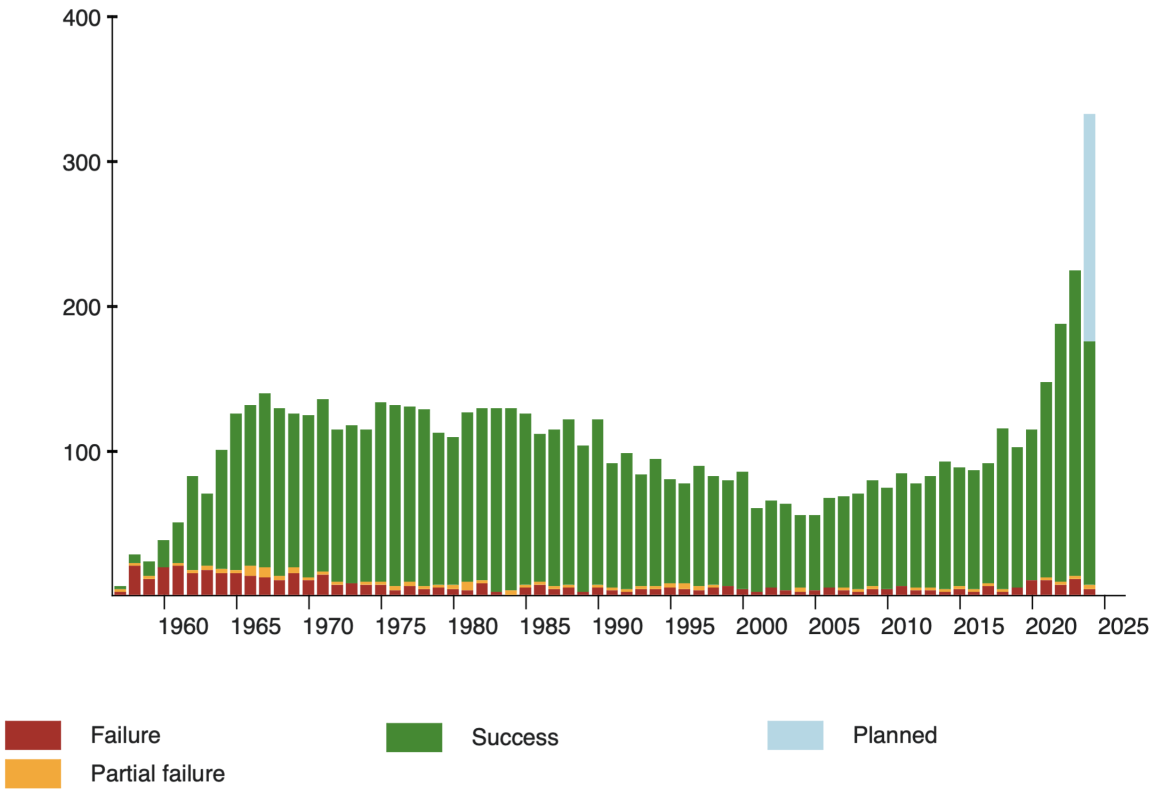

Figure 1.1 A record of the worldwide yearly orbital launch totals since 1957 to the present. Updated September 17, 2024 [1].

Lucas Hall, a wildlife ecologist at California State University, Bakersfield, is investigating the behavioral patterns of some protected bird species at Vandenberg Space Force Base [4]. Figure 1.2 shows a wildlife commotion caused by a falcon 9 rocket launch at Vandenberg. Hall reviewed a study on bird noise near commercial airports, noting how birds adapted to overwhelming jet noise by changing the tone of their song and loudness in which they sang [5]. This is just one example of how a noisy living environment may affect its inhabitants. For endangered species, could we be smothering their chance of survival under the intense pressure of rocket noise?

Figure 1.2 Birds stirred up amid a Falcon 9 rocket launch at Vandenberg Space Force Base. April 11, 2024.

At Brigham Young University, we are studying rocket acoustics to help address these issues. There are gaps in our understanding of rocket acoustics, and we are working to narrow those gaps. We envision developing a reliable model of rocket noise to help private and government space agencies answer questions and make informed decisions regarding the environmental effects of space launch operations.

1.2 RUMBLE: Rocket Acoustics Modeling Software

Blue Ridge Research and Consulting (BRRC), LLC, recently introduced a rocket acoustics modeling software program called RUMBLE. On their website, BRRC claims that RUMBLE is a "noise prediction model that produces accurate output relevant to environmental analysis of commercial space operations and space launch site facilities [6]." RUMBLE attempts to combine what is currently known about rocket acoustics to predict the sound levels experienced during space launch operations. BRRC outlines their mathematical model in their user manuals which can be found online. To compute sound pressure levels, they account for the following effects: source sound power level, forward flight effects, source directivity, the Doppler effect, geometrical spherical spreading loss, atmospheric absorption, and ground interference [7, 8].

Already we have used this tool to inform ourselves and to help inform others of the possibilities of rocket noise. Earlier this year, we published a paper concerning possible launch noise for proposed spaceports in Australia. In that article, we include a RUMBLE generated contour plot which shows sound pressure levels that could come from smaller rockets launching from one of those ports. Figure 1.3 includes that plot. A vast region of the great barrier reef is exposed to sound pressure levels between 55 dB and 85 dB [2].

RUMBLE has great potential as a tool in rocket acoustics. It could have many important uses should it prove to be accurate. The purpose of this paper is to compare launch noise predictions generated in RUMBLE with actual launch noise field measurements. This study is an attempt to verify the accuracy of the RUMBLE model. In this paper, I will compare two launch noise metrics for each rocket: Maximum Z-weighted sound pressure level (LMAX) and maximum A-weighted

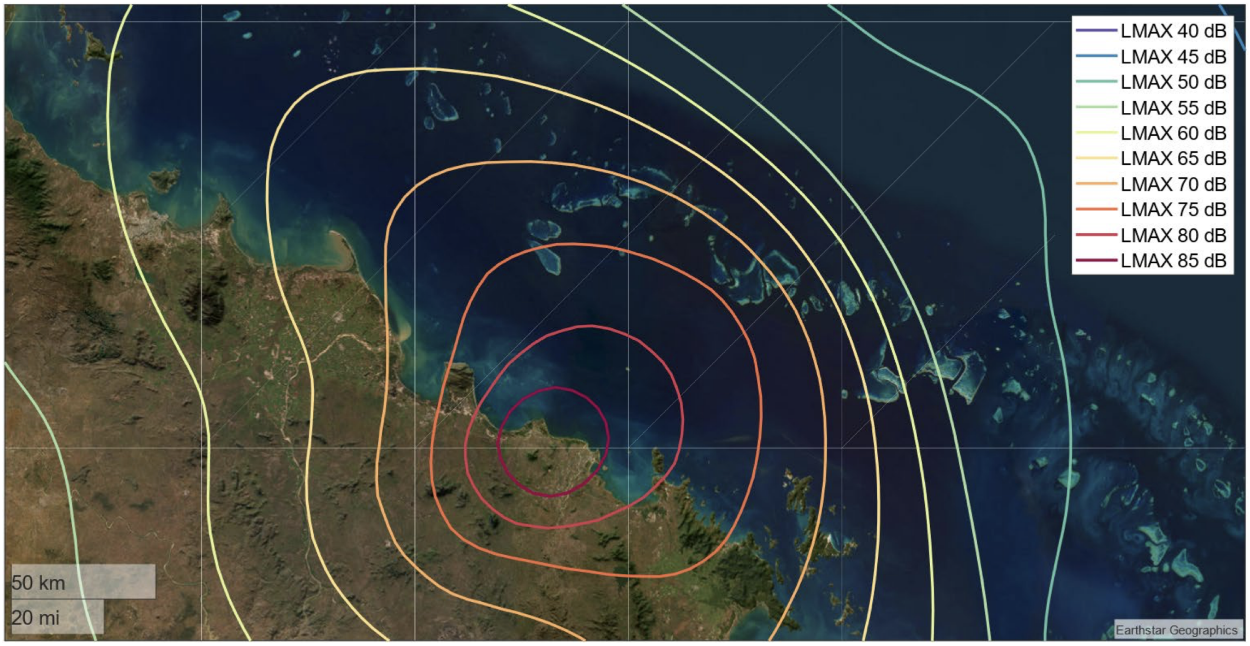

Figure 1.3 RUMBLE 3.0-predicted maximum overall sound pressure level for an Eris-like rocket launched over Australia's Great Barrier Reef [2].

sound pressure level (LAMAX). Comparisons will be made for Atlas V, Falcon 9, and Delta IV Heavy rockets. Pictures of Falcon 9 and Atlas V rocket launches are shown in figure 1.4 and 1.5.

Figure 1.4 Transporter 8 mission launch aboard the Falcon 9 rocket on June 13, 2023, from Vandenberg Space Force Base. Ground-based acoustic recording equipment, in the form of a vector intensity probe, is deployed on site.

Figure 1.5 JPSS 2 mission launch aboard the Atlas V rocket on November 10, 2022, from Vandenberg Space Force Base. Ground-based acoustic recording equipment is on display.

Chapter 2

Methods

The process for generating acoustic predictions in RUMBLE is explained in step-by-step detail. The method for collecting rocket acoustic data and computing the maximum Z-weighted sound pressure levels and the maximum A-weighted sound pressure levels are explained.

2.1 Generating Acoustic Predictions in RUMBLE

Generating acoustic predictions in RUMBLE takes several steps, and some preparation. These steps include downloading and installing RUMBLE on a computer, making trajectory and weather files in xml format, defining a spaceport, defining receptors, creating an operation to "measure," compiling a scenario, computing metric results, and generating plots. Here I will describe this step by step process, explaining each step along the way.

2.1.1 Downloading RUMBLE and System Requirements

The RUMBLE software can be found online. There is a link on the national academies web page which I will include here [9]:

https://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=4422

On that page there is a link titled "Web-Only Document 51." This link will take you to another page where you may download the RUMBLE user guide and the application itself. I recommend reviewing the user guide for at least the installation and setup of the application, as well as another reference for user instruction. I will also outline user instruction in this section. RUMBLE can only be run on Windows 7 or newer. Matlab Runtime v92 must also be installed. The newer versions may not all be compatible with the functions RUMBLE uses, so it is best to install v92 rather than other versions.

2.1.2 Trajectory and Weather Data Files

RUMBLE can take a number of external inputs including weather data, trajectory data, and user defined spacecraft. The only required user defined input is trajectory data. This, and the other external input files, must be in xml file format. Since we usually receive all of our trajectory data files as csv, we wrote a matlab script which converts these files into xml format. If you do not give RUMBLE a weather data file, calculations will be made assuming a standard atmospheric profile.

2.1.3 Create Study and Define Spaceport

Once you have your trajectory xml file ready, it's time to open the program. RUMBLE must be run as administrator. First create a new project. If a project is already open, save and close the project before creating a new one. You must come up with a name and description for your study. I named my projects after the specific launch missions I analyzed (ex. Transporter 8, JPSS2, NROL-91). Next, you must create a new spaceport. This is the launchpad from which your rocket will launch. The JPSS2 mission aboard the Atlas V rocket launched from space launch complex 3 at Vandenberg Space Force Base. I was able to find the coordinates of the launch pad online on Wikipedia, and these coordinates could be verified on google earth. The coordinates of your spaceport must be entered in decimal format. The trajectory data of your rocket will be set to start at the coordinates you define here. See figure 2.1.

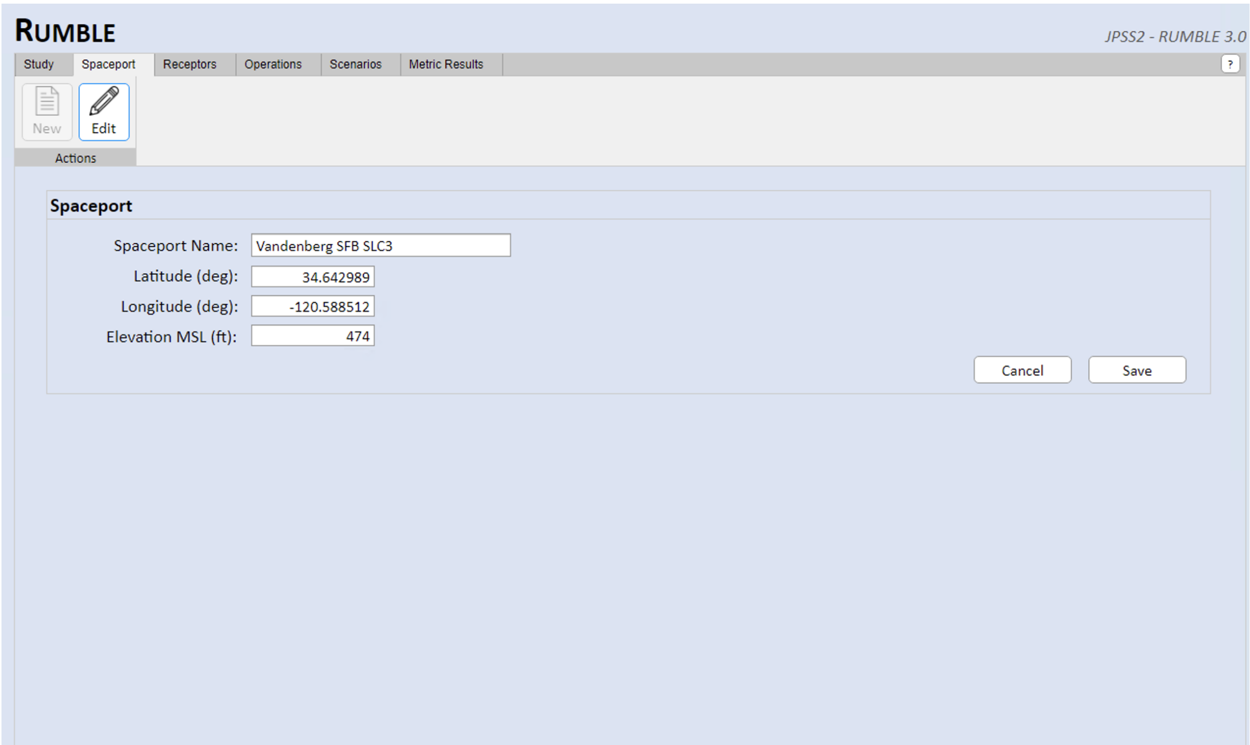

Figure 2.1 Input launch pad information by defining launch pad latitude and longitude in decimal form, and pad altitude in ft.

2.1.4 Define Receptors

A receptor is treated as a point or domain in space where RUMBLE predicts sound levels. There are two types of receptors in RUMBLE; point and grid receptors.

Point receptors analyze sound levels at a single defined coordinate in space. This type of receptor would be very convenient for making comparisons to field recordings from single microphones. However, predictions for point receptors are rounded to the nearest 5dB, meaning these predictions could be off by up to 2.5dB. It is unclear why RUMBLE rounds in this way.

A grid receptor is a domain of point receptors, and it must be used to make 2D contour plots. The user may define the number of points wide (X count) and tall (Y count) the grid will have, as well as the spacing between each point of the grid in nautical miles. The coordinate location defined by the user corresponds to the Southwest corner of the grid. The user may also define X and Y offset in nautical miles. RUMBLE will calculate sound levels at each of these grid points and then interpolate between them to make sound pressure level contour plots. Unlike point receptors, grid receptors can show sound levels down to a resolution of 1dB. For the purpose of making accurate comparisons, I used grid receptors to predict the sound levels at all of my field measurement locations. All of my grid receptors were 40 grid points tall by 40 grid points wide. I found that RUMBLE took around 90 seconds to compute sound levels for grid receptors of this size, and dramatically more time for larger grid receptors. See figure 2.2.

Although our recording stations could easily be represented as point receptors in RUMBLE, the error margin for a point receptor forced me to use grid receptors for every corresponding recording station. To do this, I first identified the coordinates of each recording station around the launch pad, and defined grid receptors with those coordinates. I defined the spacing between each grid point to be much smaller; about 0.01 nautical miles. The resulting grid receptor is 0.4 nautical miles wide and 0.4 nautical miles tall. Offsetting the grid receptor by -0.2 nautical miles in the X and Y direction centers the grid receptor over the recording station of interest. When I later made contour plots for each of these receptors, I could determine the sound pressure level more accurately to within 1 dB, by approximating which contour line the center point is closest to.

2.1.5 Operations

In defining an operation, the user chooses a launch vehicle and inputs a trajectory file. Start by selecting the box labeled "new" in the upper right. Then choose a spaceraft from the list in the tab "Choose Spacecraft". Give the operation a name. I named my operations after the name of the

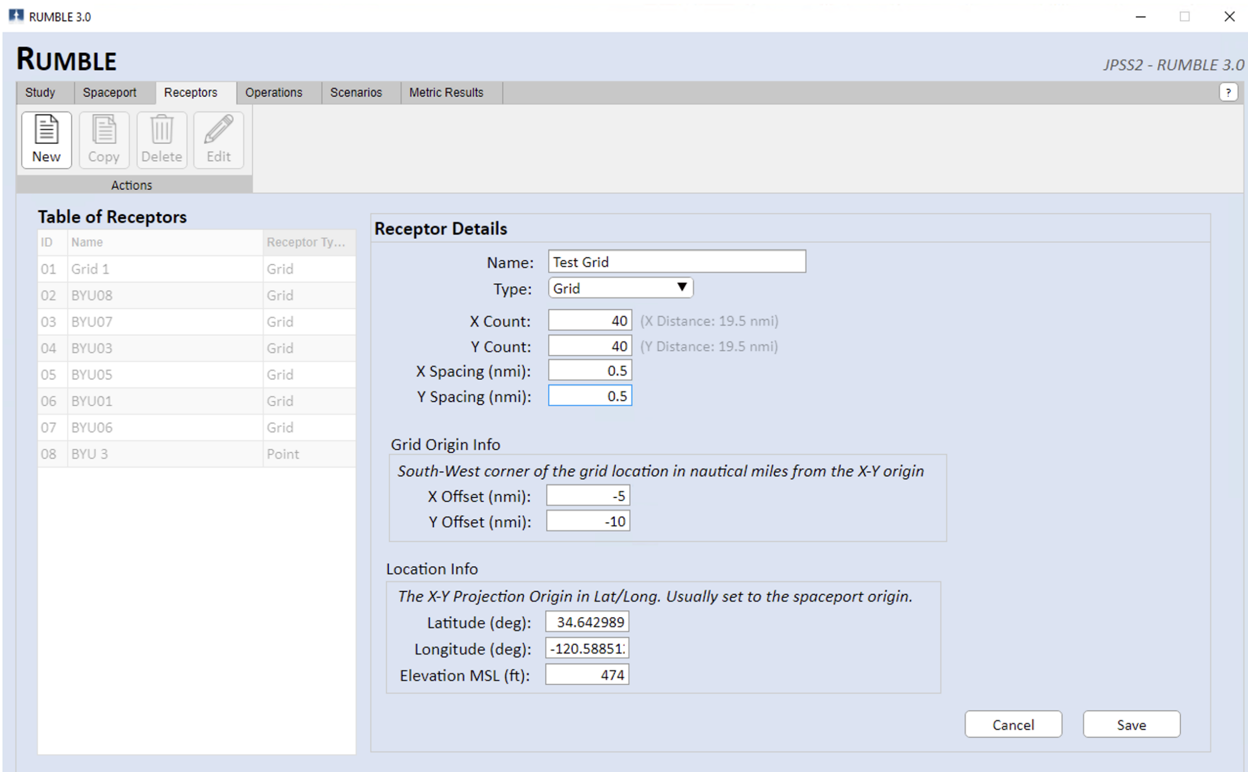

Figure 2.2 Defining a grid receptor.

missions I modeled. As for the area labeled "annual operations," input either 1 acoustic daytime or 1 acoustic nighttime. These parameters affect other metrics like sound exposure level, day-night average sound level, and community noise level equivalent. You can put in other values to test these metrics, but for our purposes one acoustic daytime will do. Finally, in the drop-down menu by "Trajectory," click "Browse". Now find the xml trajectory file you created for this launch and click "create." See figure 2.3

2.1.6 Scenarios

Generally speaking, rocket launches rarely include more than one launch vehicle in flight at a time. However, in the scenarios tab, we can define a scenario with multiple launch operations happening at the same time. For the purpose of this study, I only ever included one launch operation in every

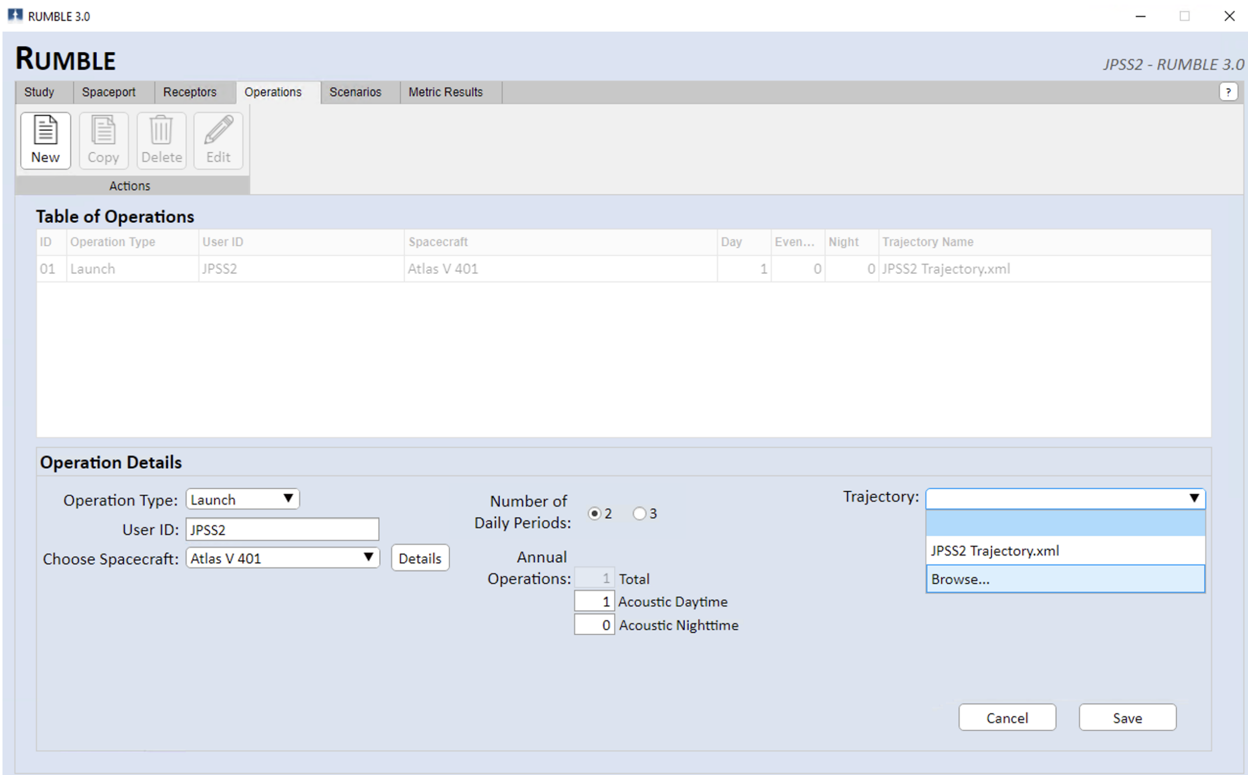

Figure 2.3 Create an operation. Upload a trajectory file and select a rocket model.

scenario. Start by creating a new scenario. Jive the scenario an appropriate title. Check the box that says "Add new spacecraft operation group(s)." Then click next. In the box below where it says "Add new group" type a name for the group of potential operations this scenario will have, and click add. See figure 2.4. Now In the box to the left of the arrows, click on an operation to be added the the operations group. Then click on box with the two left pointing arrows. See figure 2.5. Operations must be added to operation groups one at a time. Finally click "next" and "save." See figure 2.6.

2.1.7 Computing Metric Results and Making Contour Plots

Finally, it is time to define and compute the metric results. Select the metric to be calculated. Then choose a scenario to analyze and one of the previously defined receptors. If you have weather data, load that xml file here as well. If no weather data is imported, all computations will be made

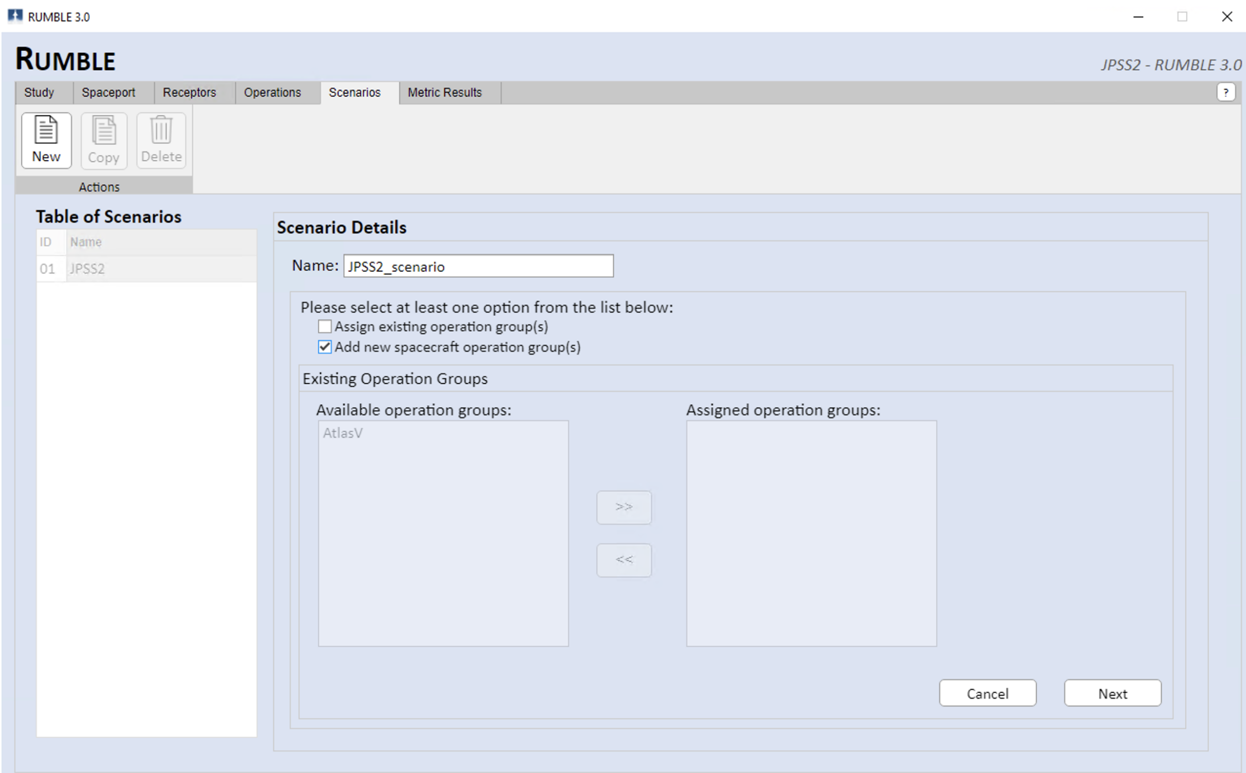

Figure 2.4 Create a new scenario.

assuming a standard atmospheric profile. Once saved, click on the newly defined metric result in the table on the left and click "Run." After the program has completed it's calculations there should appear a check mark in the leftmost column of the table. With the metric result highlighted, you can now create contour plots of the calculated metrics. These contour plots will be overlayed on a map of your choosing. See figure 2.7

2.2 Overview of method for collecting rocket acoustics data

Capturing the sound levels of a rocket launch requires extensive planning in advance. For the most part, we cannot be at the recording stations near the launch pad for obvious safety reasons. Also, we usually want to set up more stations than we have people to manually trigger the recordings.

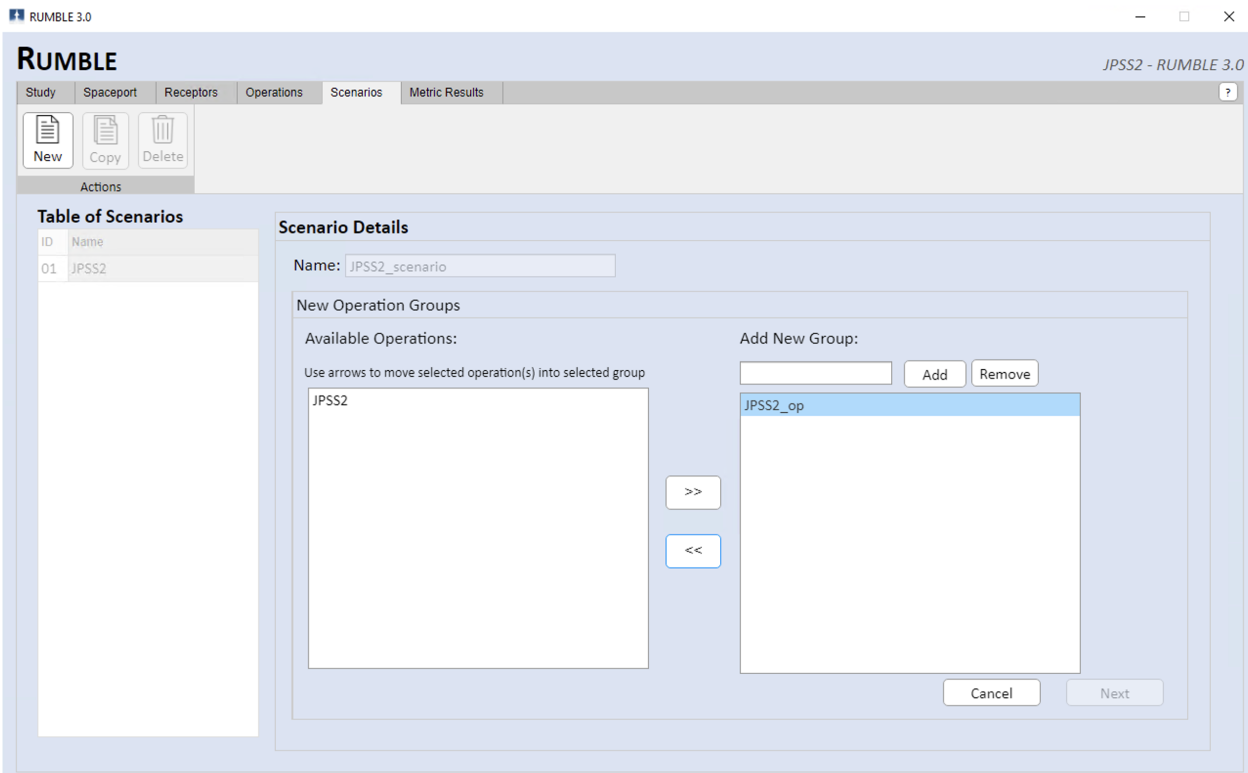

Figure 2.5 Name the operations group.

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Therefore, our recording devices are set up to be time or amplitude triggered. Days before a rocket launch, we plan locations, assemble data acquisition hardware, and eventually set up the recording stations at our planned locations. After, we collect all hardware, and begin analyzing the data.

2.3 Calculating Z and A-weighted Sound Pressure Levels

Sound pressure is a localized measurement often with units of pascals (Pa). The observed sound pressure will vary with distance to a sound source; the greater the distance from the source, the lesser the sound pressure caused by the source. In acoustics, we generally compare sound pressure on a logarithmic scale with a reference pressure of 20 μPa. This is called the decibel scale and we

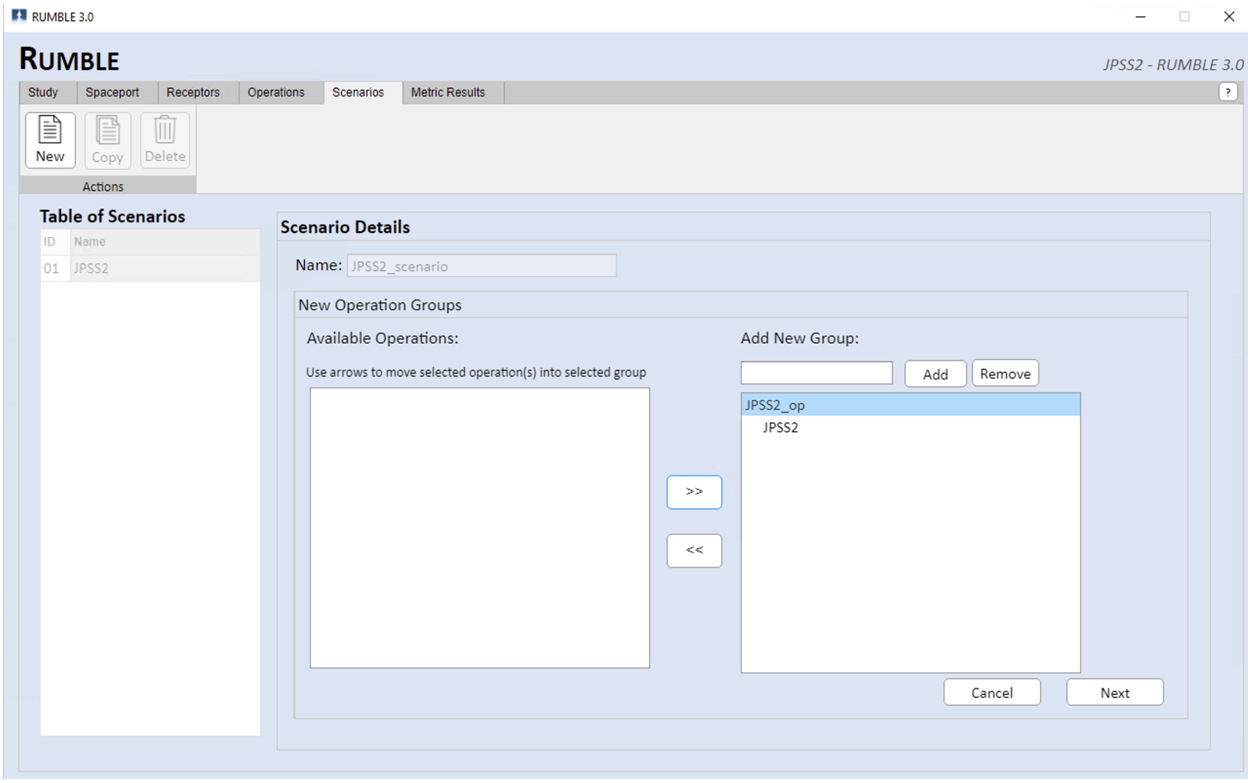

Figure 2.6 Add operations to the operations group and save scenario.

give it units of decibels (dB). The sound pressure level is the sound pressure on the decibel scale. The formula

$$\mathrm{SPL(dB)} = 20\log_{10}\left(\frac{P}{20\ \mu\mathrm{Pa}}\right) \tag{2.1}$$

calculates the sound pressure level, where P is some input sound pressure in pascals. On this scale, a 6 dB increase algebraically corresponds to a doubling of sound pressure. Although the reference pressure in the denominator can be changed to other values potentially significant to other studies, in acoustics, the standard is 20 µPa.

To set the stage for discussing the application of weighting functions to acoustic data, I'll first clarify what a frequency weighting function is. Frequency weighting functions are used to emphasize a specific range of frequencies within a broader spectrum. They significantly reduce the amplitude of frequencies outside the targeted range, making the chosen frequencies more prominent

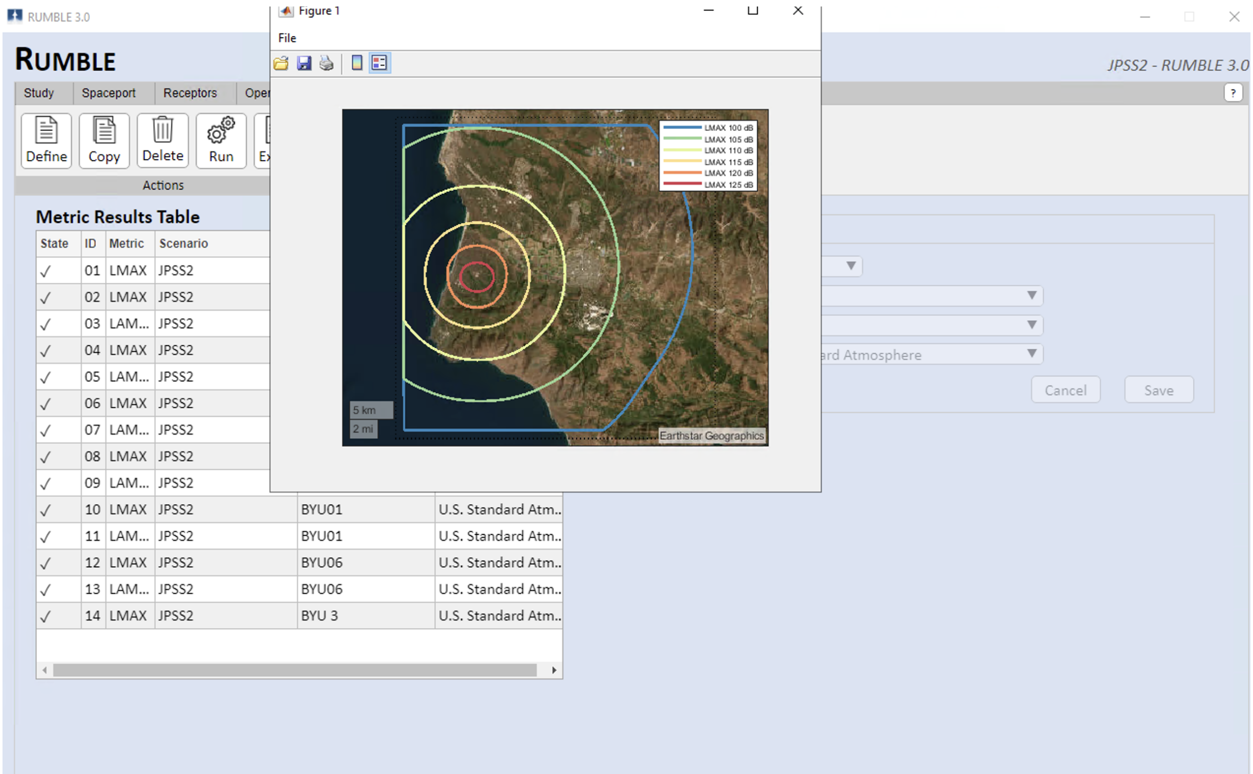

Figure 2.7 Example of a contour plot generated after computing a metric result.

in the data. If no weighting curve is applied, the data set is unweighted. In acoustics, unweighted, flat-weighted, and Z-weighted are terms used interchangeably. They all mean the same thing as unweighted. In this paper, I will use the term Z-weighted when referring to an unweighted dataset.

A large majority of rocket noise peaks in the sub 20 Hz range, which is below the range of human hearing. However, when investigating the potential effects of rocket noise on human hearing, or other wildlife, raw maximum sound pressure levels will not always be relevant. Instead, we must look at maximum sound pressure levels of frequencies in the audible range. To do this, we apply a weighting curve to our measurement recording. I compare A-weighted levels , which have frequently been used to analyze sound exposure in the audible range of human hearing. The formula for the A-weighting curve

$$R_A(f) = \left(\frac{12194^2 f^4}{(f^2+20.6^2)\sqrt{(f^2+107.7^2)(f^2+737.9^2)(f^2+12194^2)}} \right) \tag{2.2}$$

is a function of frequency. I multiplied this function to the frequency power spectrum of each acoustic waveform to A-weight the data. As can be seen from Figure 2.8, the A-weighting curve significantly reduces the amplitude of frequencies above 10,000 Hz and below 1000 Hz.

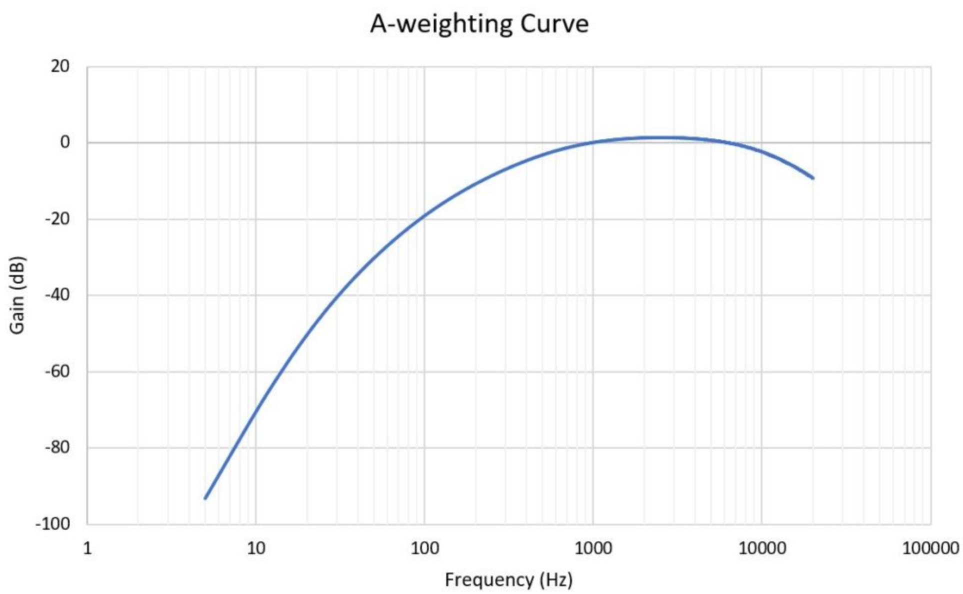

Figure 2.8 Effect of A-weighting curve on the frequency domain

To calculate maximum A-weighted sound pressure level, we first transform our recorded waveform into a frequency spectra. This is done in matlab with an fft (fast Fourier transform). Integrating over the A-weighted frequency spectra gave me A-weighted maximum sound pressure level. Another way to calculate maximum Z-weighted sound pressure level is, again, to integrate over the frequency spectra of a given waveform, this time applying no weighting curve.

Chapter 3

Results

This section will include results in tabulated form. Two tables comparing Z-weighted levels and A-weighted levels are presented for each rocket. For clarity, RUMBLE labels Z-weighted levels as LMAX, and A-weighted levels as LAMAX.

The JPSS2 mission launched on November 10, 2022 aboard the Atlas V rocket. The average and median differences between measured and predicted Z-weighted levels are both 0 dB. The average and median differences between measured and predicted A-weighted levels are -2.33 dBA and -2.5 dBA.

The NROL-91 mission launched on September 24, 2022 aboard the Delta IV Heavy rocket. The average and median differences between measured and predicted Z-weighted levels are -1.67 dB and -2 dB. The average and median differences between measured and predicted A-weighted levels are 1 dBA and -0.5 dBA.

The NROL-91 mission launched on September 24, 2022 aboard the Delta IV Heavy rocket. The average and median differences between measured and predicted Z-weighted levels are 0.67 dB and 0 dB. The average and median differences between measured and predicted A-weighted levels are -1.17 dBA and -1 dBA.

Table 3.1 JPSS2 Atlas V Z-weighted Levels

Station	Distance (m)	RUMBLE LMAX (dB)	Measured LMAX (dB)	Difference (dB)
1	206	145	146	-1
3	2855	122	122	0
5	2650	123	122	1
6	280	143	143	0
7	1120	130	129	1
8	1300	127	128	-1

Table 3.2 JPSS2 Atlas V A-weighted Levels

Station	Distance (m)	RUMBLE LAMAX (dBA)	Measured LAMAX (dBA)	Difference (dBA)
1	206	131	130	1
3	2855	102	104	-2
5	2650	103	106	-3
6	280	128	130	-2
7	1120	113	116	-3
8	1300	111	116	-5

Table 3.3 NROL-91 Delta IV Heavy Z-weighted Levels

Station	Distance (m)	RUMBLE LMAX (dB)	Measured LMAX (dB)	Difference (dB)
1	1168	132	133	-1
2	947	134	132	2
3	667	138	139	-1
4	1822	128	131	-3
5	1466	130	133	-3
6	1555	130	134	-4

Table 3.4 NROL-91 Delta IV Heavy A-weighted Levels

Station	Distance (m)	RUMBLE LAMAX (dBA)	Measured LAMAX (dBA)	Difference (dBA)
1	1168	121	122	-1
2	947	124	115	9
3	667	128	126	2
4	1822	116	118	-2
5	1466	118	120	-2
6	1555	118	118	0

Table 3.5 Transporter 8 Falcon 9 Z-weighted Levels

Station	Distance (m)	RUMBLE LMAX (dB)	Measured LMAX (dB)	Difference (dB)
1	528	139	139	0
2	386	142	143	-1
7	1253	131	128	3
9	3681	122	120	2
10	3696	122	122	0
11	4080	120	120	0

Table 3.6 Transporter 8 Falcon 9 A-weighted Levels

Station	Distance (m)	RUMBLE LAMAX (dBA)	Measured LAMAX (dBA)	Difference (dBA)
1	528	124	125	-1
2	386	127	128	-1
7	1253	115	115	0
9	3681	100	103	-3
10	3696	102	105	-3
11	4080	101	100	1

Chapter 4

Discussion of Results and Conclusion

Researchers at Blue Ridge Research and Consulting llc claim that RUMBLE is the most accurate orbital launch acoustics prediction software. The results of my comparisons communicate confidence in the accuracy of the RUMBLE model. However, there is potential room for improvement. I will first analyze the overall differences between measured and predicted sound levels. I will then evaluate my methods. Finally, I will discuss RUMBLE's inappropriate use of the Doppler effect and steps moving forward.

The greatest differences between measured and RUMBLE predicted sound levels are 4 dB for z-weighted and 9 dBA for A-weighted levels. For reference, every 6 decibel increase corresponds to a doubling of sound pressure and a quadrupling of sound intensity. 9 dBA is a highly significant error. However, it is possible that this extraordinary difference comes from poorly calibrated measurement hardware. Seeing that stations farther from the launch pad consistently measured higher levels, this is likely the case.

The average difference between measured and RUMBLE predicted z-weighted levels is -0.33 dB, while the average difference for A-weighted levels is -0.83 dBA. Corresponding median values are 0 dB and -1.5 dBA. The median values are more representative in this case due to the major outliers in the dataset. Discarding the 9 dBA outlier, the average becomes -1.41 dBA. At the end of this study, I find that RUMBLE very accurately predicts maximum Z-weighted sound pressure levels, but under-predicts maximum A-weighted levels.

Vandenberg Space Force Base, where all of our measurements for these comparisons were collected, is notorious for extreme unpredictable weather swings on base. In nearby Lompoc, it may be sunny and 85, while on base, less than 50 miles away, there is thick fog, wind and 60 degree temperatures. This pattern of a chaotic and inconsistent atmospheric profile has been shown to effect the sound levels we measure. Atmospheric turbulence alone has been observed to affect sound levels by up to 8 dB over a 500 ft stretch [10]. Investigating the effect of weather on RUMBLE predictions could be an entire study of its own, and should be done as a continuation of this study.

A-weighted calculations differ by 1.5 dBA. It is very likely that this median 1.5 dBA difference comes from RUMBLE's use of the Doppler effect. The Doppler effect in acoustics applies to solid-gas interfaces. Although the vibration of the solid body of the rocket should produce some sound that could be Doppler shifted, the overwhelming majority of sound power comes from the unique plume dynamics of the exhaust. The plume is not moving at the speed of the rocket. The exhaust is initially moving at supersonic speeds opposite the direction of motion of the rocket. Soon after, the propellant colliding with the atmosphere turns into a tumbling turbulent flow region. It is this turbulent flow region which is the primary source of rocket noise [5]. This means that the average velocity of the sound source is likely zero, and therefore cannot be Doppler shifted. The observed drop in frequency as the rocket moves away from an observer is only attributed to non-linear propagation effects [11].

Now let's consider how the use of the Doppler effect could affect RUMBLE predicted Z and A-weighted levels. Since Z-weighted levels have no weighting curve applied, a shift in the observed frequencies would not make a difference in Z-weighted levels. The maximum sound pressure would be the same level, although attributed to lower frequencies. Since an A-weighting curve reduces the levels of lower frequencies, A-weighted levels should show lesser values with the Doppler effect applied. This is what I find in my comparisons. RUMBLE Z-weighted levels show little to no difference, while A-weighted levels under-predict compared to field measurements. The use of the Doppler effect to predict sound levels of rockets is conclusively incorrect.

The results of comparing RUMBLE generated sound pressure level predictions with field measurements show with great confidence the accuracy of the RUMBLE model. However, the model has at least one flaw. RUMBLE inappropriately uses the Doppler effect, causing A-weighted levels to under-predict. This study should continue with the incorporation weather data.

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